National Physical Laboratory

EMPRESS Workshop
Enhanced temperature measurement techniques for improved process control
22 March 2017
Advanced Forming Research Centre, UK
Organised by AFRC and NPL

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TEMPERATURE METROLOGY FOR PROCESS EFFICIENCY

WP4: Traceable combustion temperature measurement

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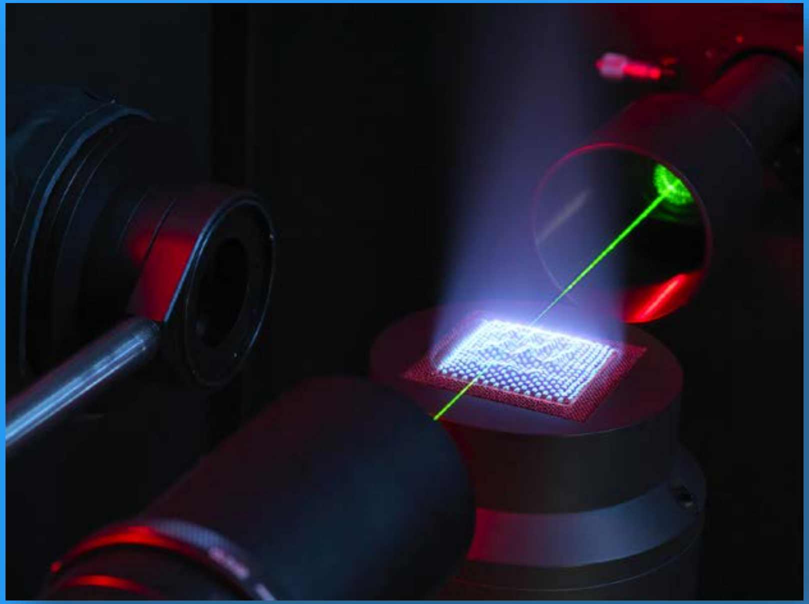

ADVANCED FORMING RESEARCH CENTRE
UNIVERSITY OF STRATHCLYDE

Institute of Measurement and Control

IOP Institute of Physics
Instrument Science and Technology Group

Measuring combustion temperatures: Why is it important?

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The temperature of any combustion process critically affects:

- Chemical reaction rate
- Process efficiency
- Pollutant levels
- Product quality
- Rate of failure mechanisms

Achieving the correct temperature is critical

Qu: Why aren't combustion temperatures routinely measured?

- Extremely harsh environment
- Probe survivability
- Flame evolution easily perturbed
- Access is challenging

- Model combustion process
- Validate model – test rig
  - Scaled down
  - Probe access
  - Heavily instrumented

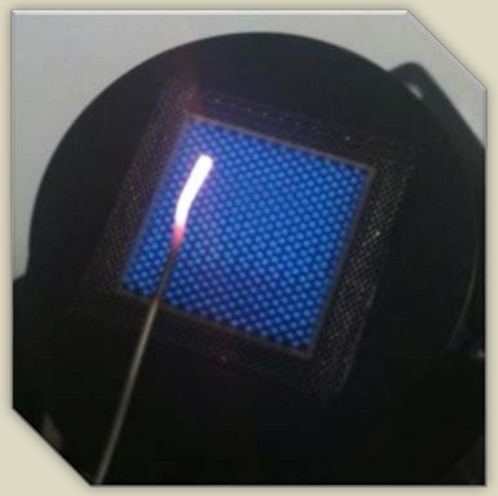
This is where we can help – good metrology.

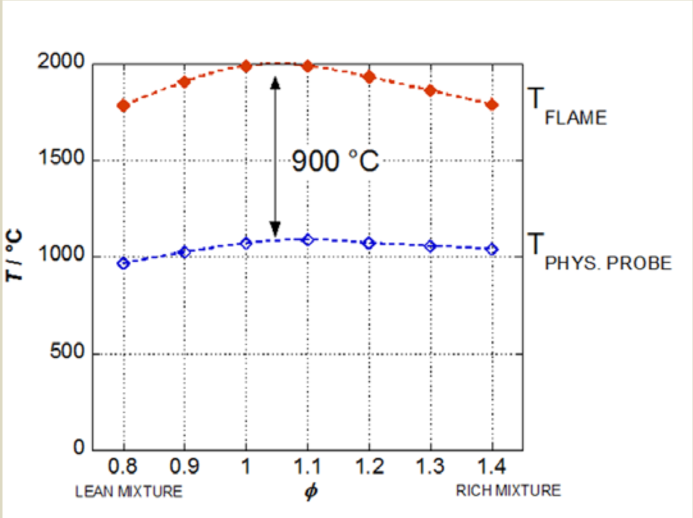
WP4: Physical and optical probes

Physical probes:

- Perturb the flame
- Give probe T <u>not</u> flame T
- Don't last very long
- Access is challenging
- Slow response speed

Example





Optical probes:

- Emitted light can give T information
- Depends on 'type' of excitation
- Non-intrusive
- High response speed
- Access is still challenging
- Technically complex
- Needs calibration

Calibration source:

Region of hot gas of known T and composition traceable to ITS-90.

Calibrate optical probe by measuring in this region.

WP4: Traceable Combustion Temperature Measurement

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European project to enhance process efficiency through improved temperature measurement:

1. STD flame calibrated at NPL
2. Partner organisations – developing novel optical combustion thermometers
3. STD flame – circulated to partners
4. Comparison of techniques – publication
5. NPL facility available for others

DTU Technical University of Denmark

UV/IR spectroscopy

NPL

Portable STD Flame
Rayleigh scattering

Universidad Carlos III de Madrid

CEM CENTRO ESPAÑOL DE METROLOGÍA

IR hyperspectral imaging

UNIVERSITY OF OXFORD

LIGS

Gavin Sutton, Alexander Fateev, Paul Ewart, Sergio Sánchez Carballido, Miguel Rodríguez, Guillermo Guarnizo, Juan Meléndez, Dolores del Campo, Benjamin Williams.

NPL: Combustion Temperature Standard

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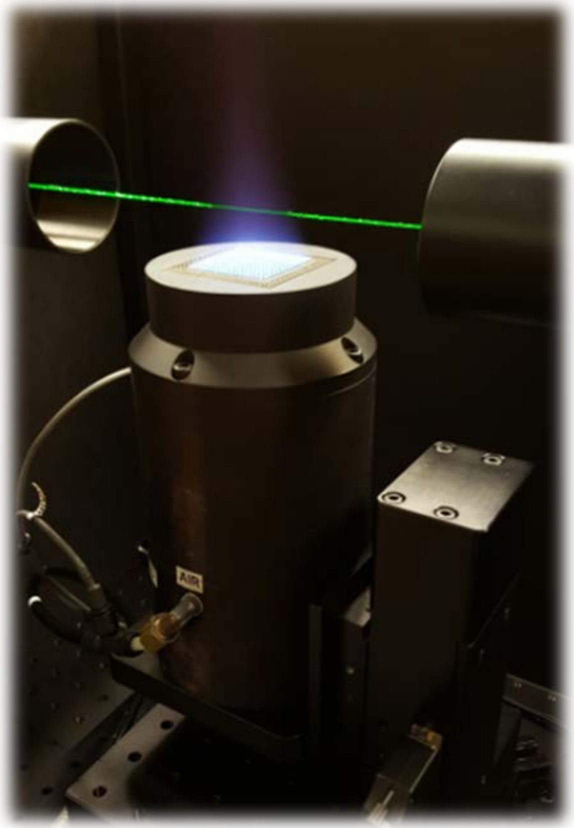
Requirement 1

Stable, reproducible region of hot gas of known temperature and species:

- Hencken Burner – diffusion flamelets
- Propane / air flame – $\{0.8 < \phi < 1.4\}$
- Low uncertainty flowmeters - $U_r(flow) < 0.5\%$
- Known post flame composition
- Traceable to ITS-90
- Portable
- Reproducible temperature - $U_r(T) < 0.5\%$



$$\phi = \frac{\left(V_{fuel}/V_{air}\right)}{\left(V_{fuel}/V_{air}\right)_{Stoichiometric}}$$

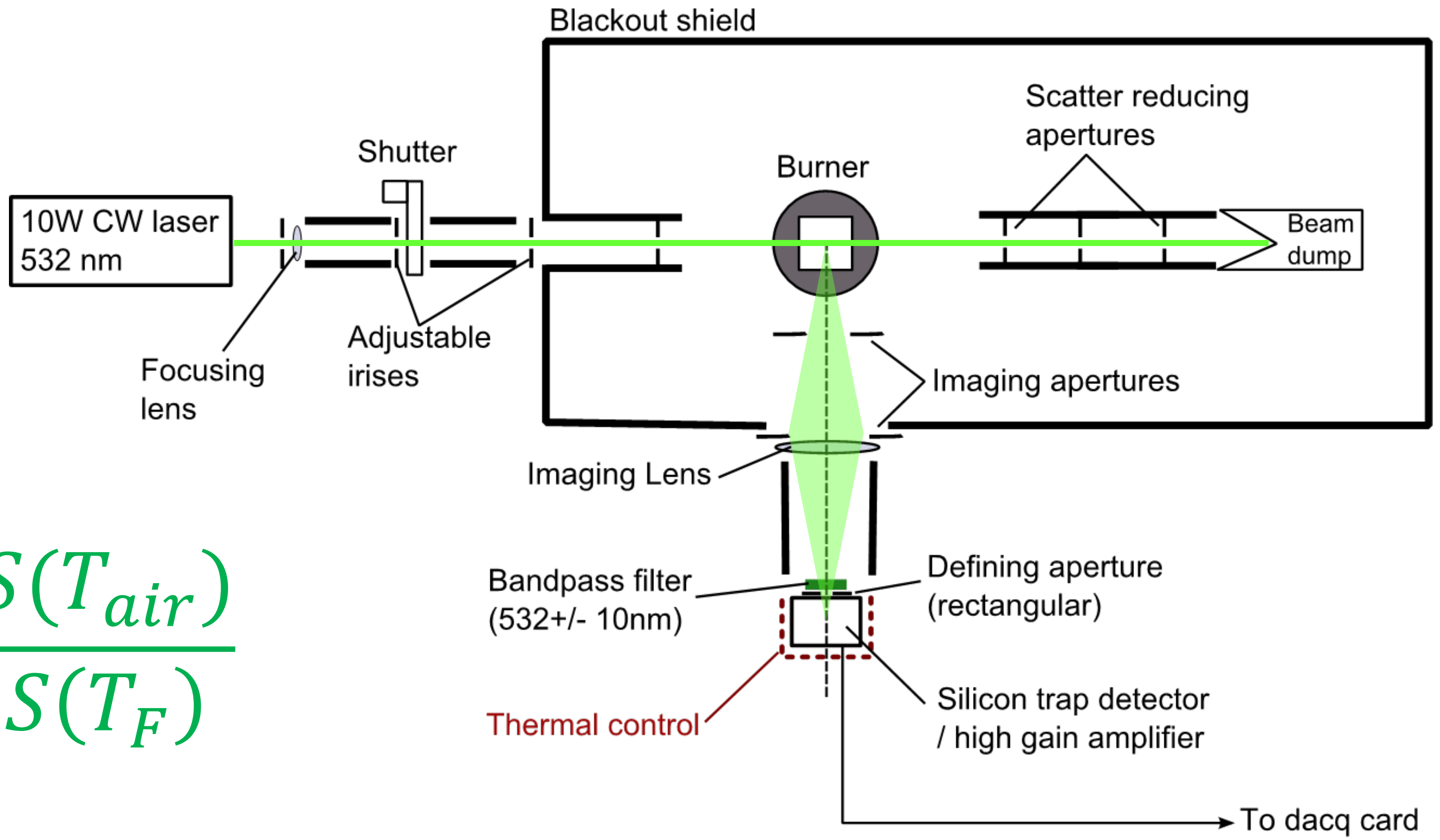
Stoichiometric → fuel/air ratio for a balanced reaction (i.e. no excess oxygen)

NPL: Combustion Temperature Standard

<u>Requirement 2</u>

Traceable, non-perturbing temperature measurement:

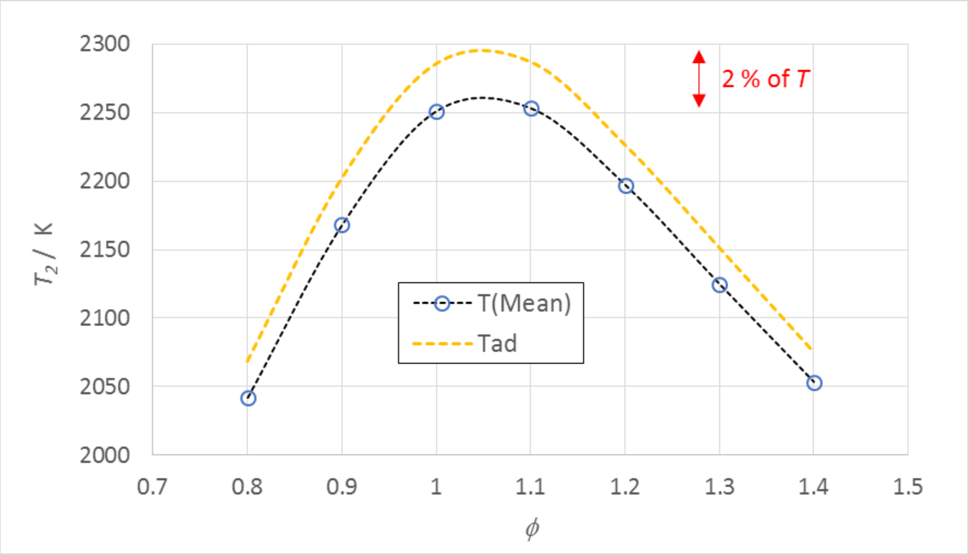
- Rayleigh scattering thermometry

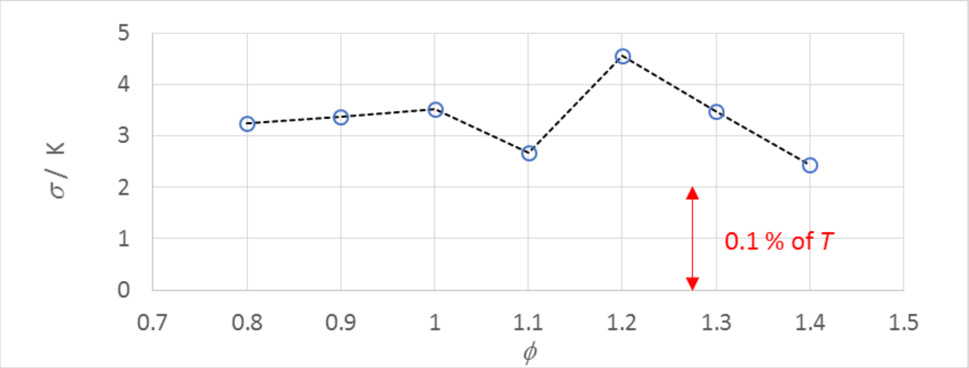


$$T_F = \delta \frac{S(T_{air})}{S(T_F)}$$

NPL: Combustion Temperature Standard

Results: Rayleigh scattering thermometry





Mean temperature 20 mm above the burner centre

- 10 measurements, over 3 months.
- Temperature lower than maximum due to heat loss to burner (< 2%).
- Reproducibility 4 K / 0.2 % (1 σ).
- Access to fixed temperatures over the range 2040 K to 2260 K.
- Repeat measurements do no correlate with ambient test conditions

NPL: Combustion Temperature Standard

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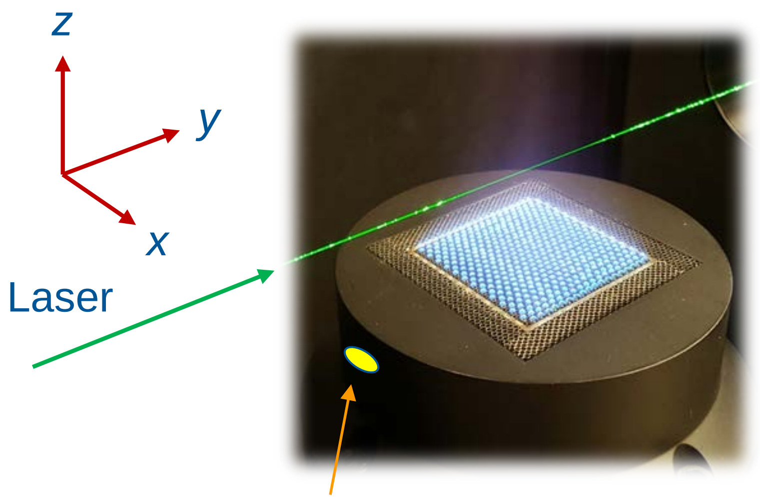
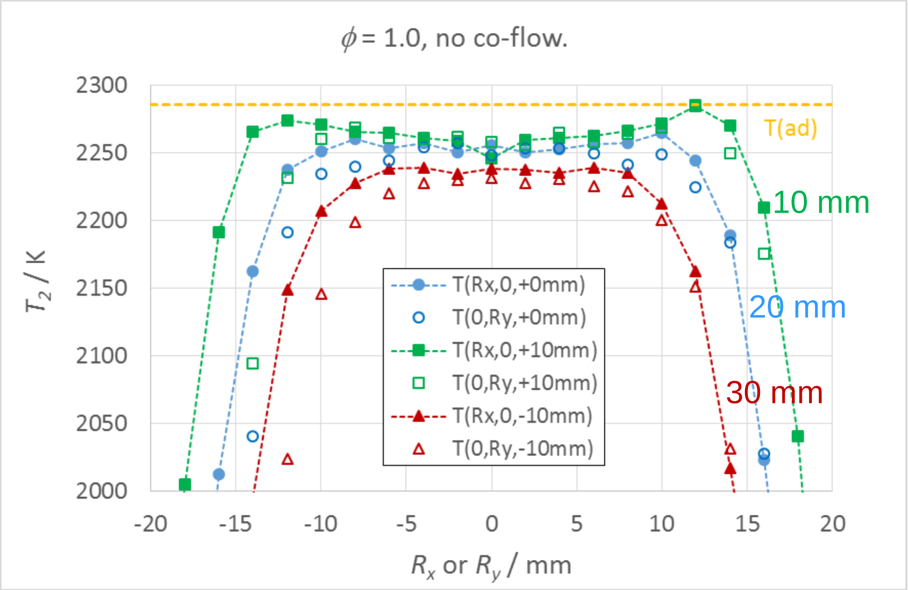
Results: Temperature profiles

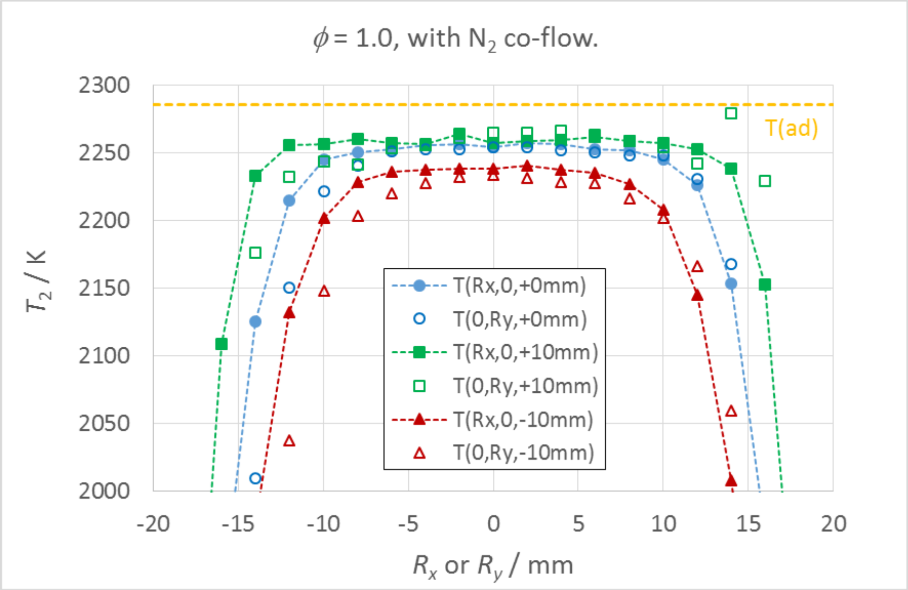
- x and y scans
- 3 heights above the burner:
  - 10 mm, 20 mm and 30 mm
- With / without N_2 co-flow

- Flatter flame and less noise with co-flow
- Temperature falls with increasing height



spot on burner showing
laser entry orientation





UC3M / CEM: Hyperspectral imaging

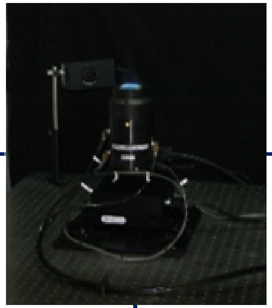
- Michelson interferometer: FTIR, MIR band, FPA (imaging)
- Imaging emission spectroscopy:
  - Flame temperature maps, T (K)
  - Species concentrations, Q (ppm·m), i.e. CO_2, CO
  - RT model to simulate flame emission
  - Iterative fitting to retrieve both T and Q for <u>each</u> pixel
- Specific developments:
  - Adaptation of system for flames: dynamic range, calibration, spectral/spatial resolution
  - Post-processing procedures
  - Correct for flame flicker
  - Data size reduction and S/N improvement
  - Estimation of uncertainty by Monte Carlo method
  - Measurements on the NPL STD flame

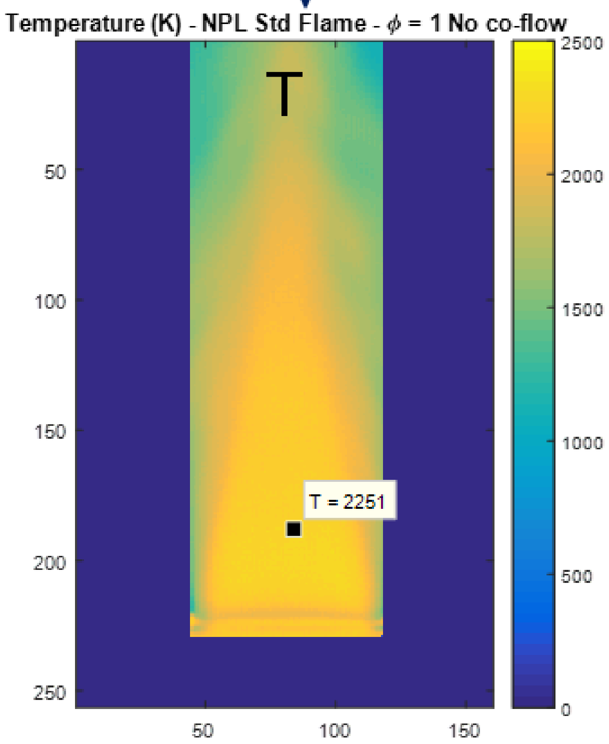
Bunsen burner flame

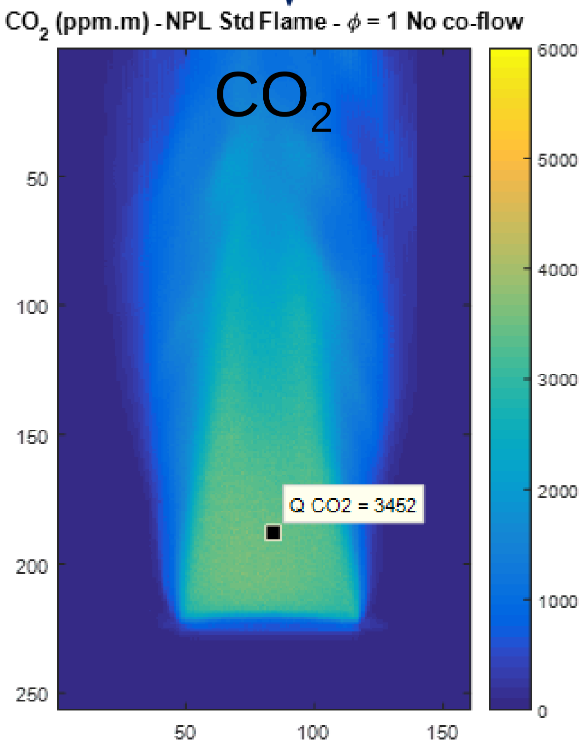
UC3M / CEM: Hyperspectral imaging

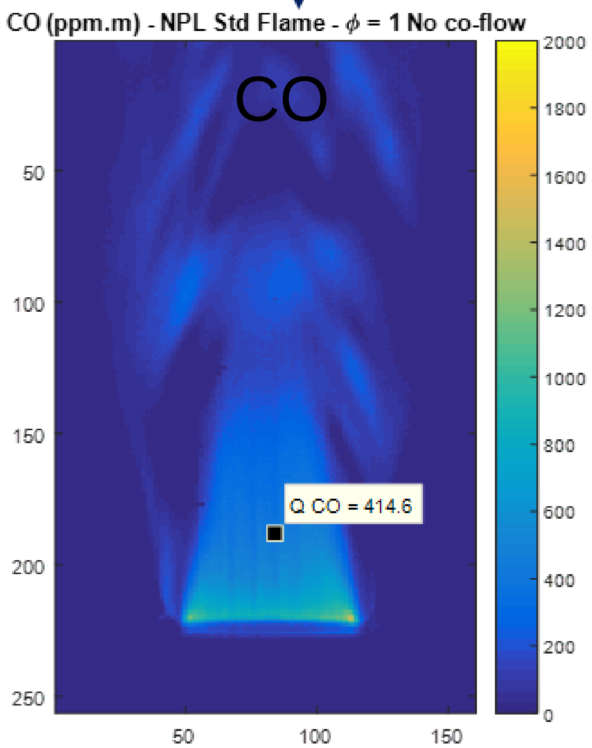
Measurements on the NPL STD flame

Temperature and
concentration maps φ = 1





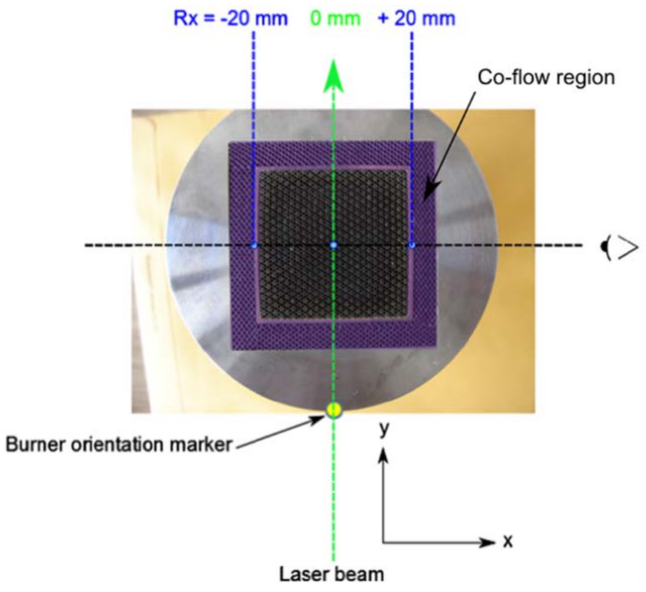




Demonstrates: T uniformity <u>close</u> to burner and ‘slow’ conversion of CO to CO_2

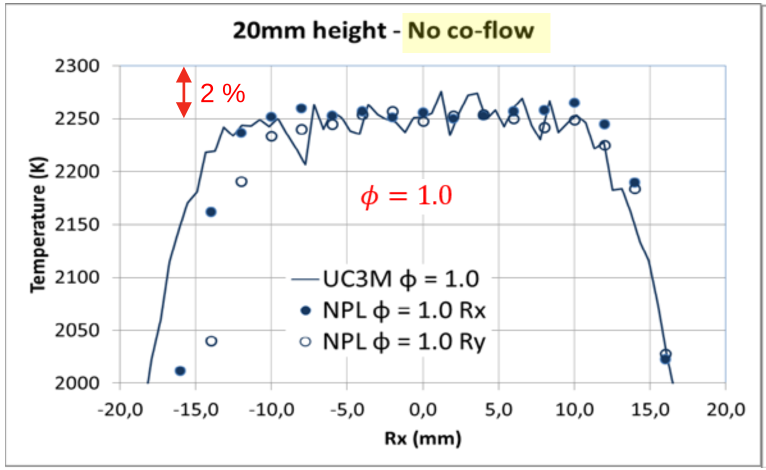
UC3M / CEM: Hyperspectral imaging

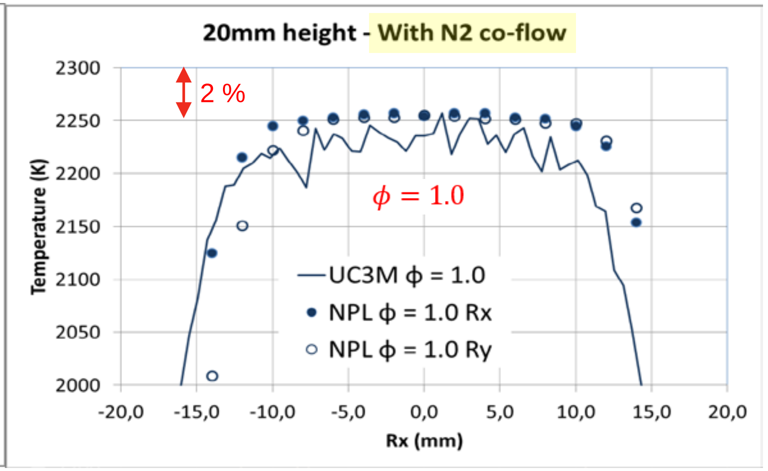
Measurements on the NPL STD flame



Temperature comparison, $\varphi = 1.0$:

- σ (± 1cm): UC3M ≈ 9K, NPL ≈ 5K
- No co-flow: Excellent agreement
- With N_2 co-flow: minor differences
- Demonstrates need for validation via STD flame

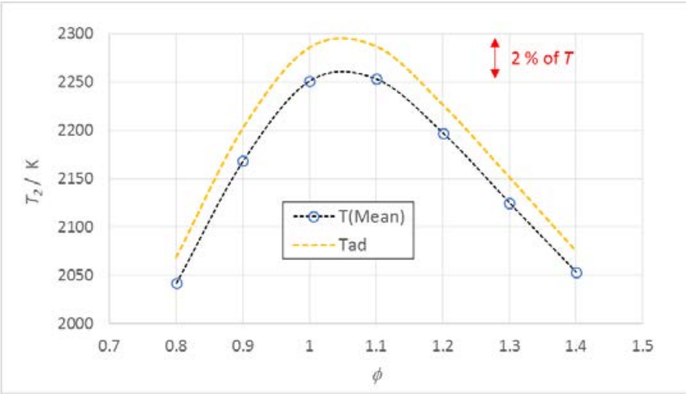




UC3M / CEM: Hyperspectral imaging

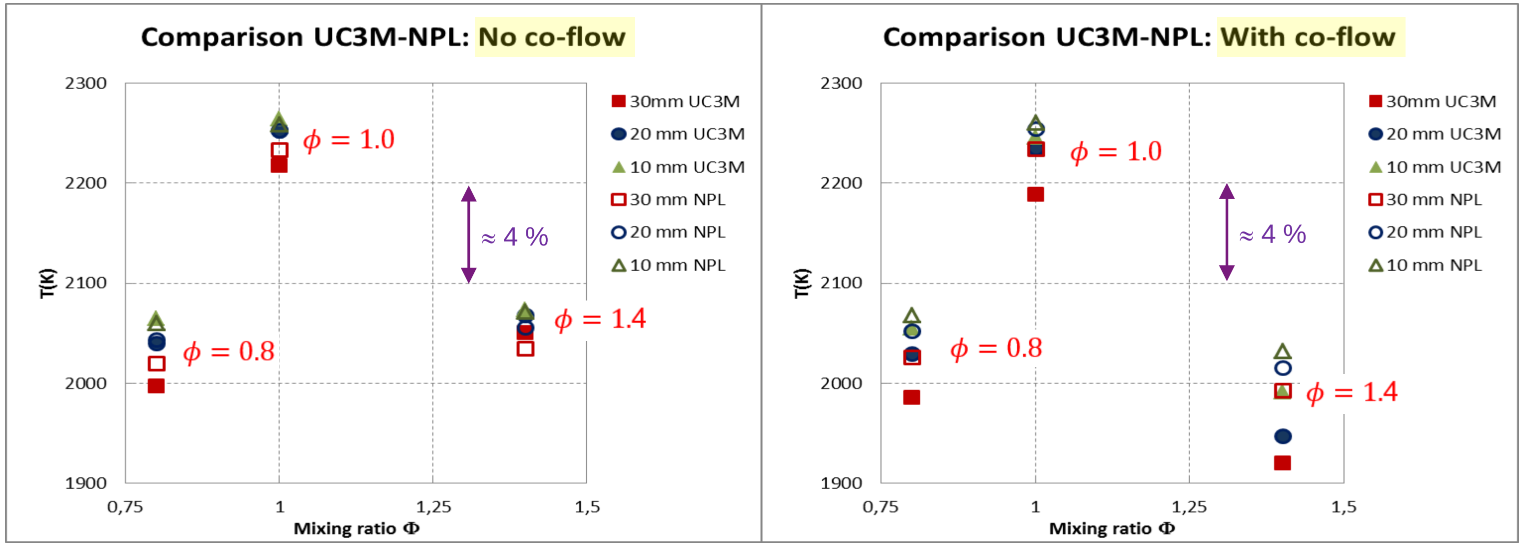
Measurements on the NPL STD flame

Remember T(φ) curve….



Temperature comparison versus φ:

- No co-flow: Excellent agreement
- With N_2 co-flow: minor differences
- Demonstrates need for validation



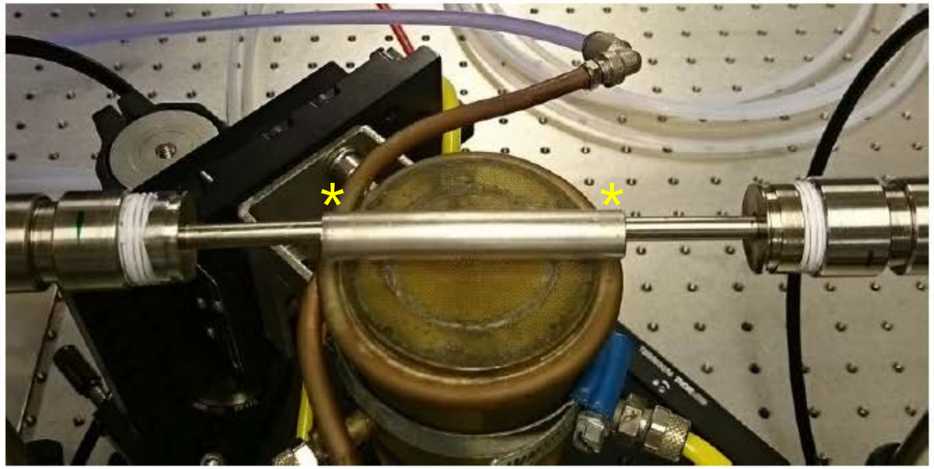
DTU: UV spectroscopy

Flame Thermometry – Kaminski burner (CH_4 / air).

- Determine UV absorption spectra in real combustion:
- Hot gas cells – uniform gas path, known T and species.
- CO_2 and H_2O mainly
- O_2, OH, NO also
- New unique high-temperature data sets
- Novel in-situ UV measurement approach - opens wide possibilities for process control and sensor development where gas temperature is important

Flat flame burner:
UV absorption measurement

Flat flame burner: UV absorption path shown, gas path covered for reference measurements.

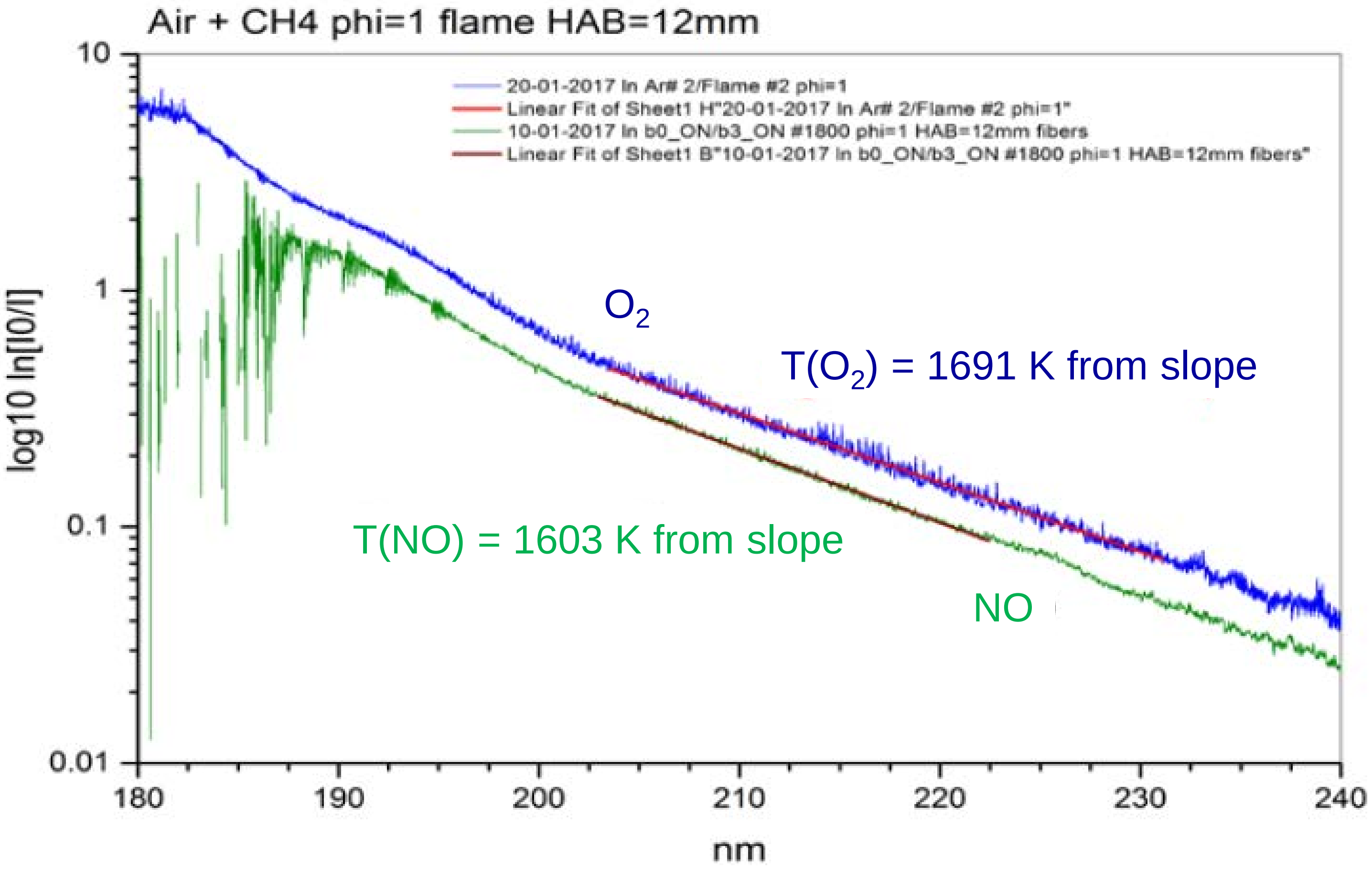


DTU: UV spectroscopy

Flame Thermometry – Kaminski burner (CH_4 / air).

Example:

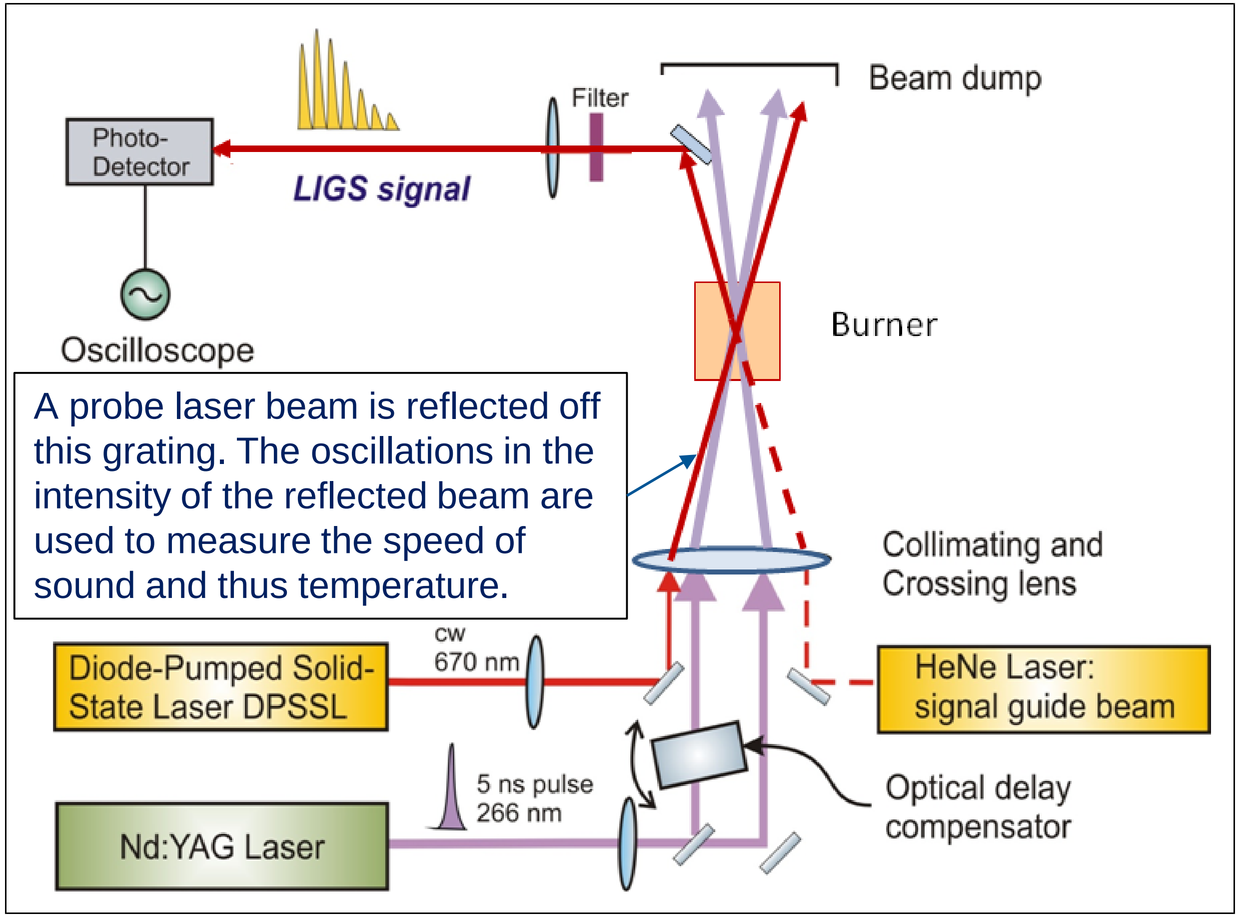
- Temperature measured with O_2 and NO bands.
- Good agreement.



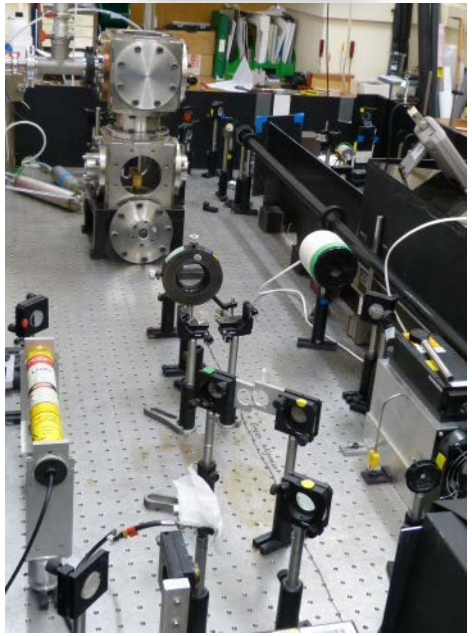
UOX: LIGS
(Laser Induced Grating Scattering) thermometry

Current experiments: LIGS signals generated in NO in a flame

- Sudden perturbation of the gas (due to energy absorption from the laser gratings) launches two counter-propagating sound waves, that modulate the grating reflectivity.



Experimental layout for LIGS in NO in a flame

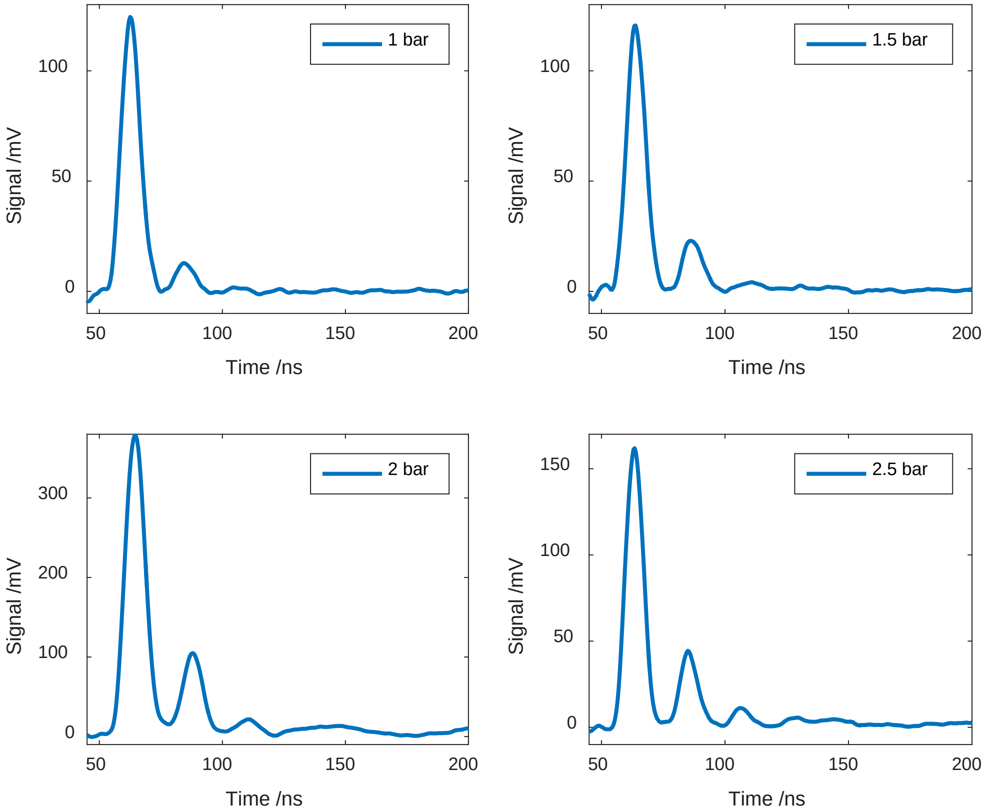


Optical arrangement: laser system on RHS, LIGS optics in foreground and burner in top left of photo.

UOX: LIGS thermometry

Results: LIGS signals generated in NO in a flame (T ≈ 2300 K).

- Signal versus pressure shown below
- Has demonstrated ability to measure *T* and *P* simultaneously
- Point measurement / not radiometric – fit shape not absolute magnitude



Experimental data showing LIGS signals
from NO in a flame at different pressures

Future experiments will use infra-red LIGS using combustion-generated H_2O in the post-reaction zone.

UOX: LIGS thermometry

Improvement to state-of-the-art

- LIGS provides the most precise non-invasive, spatially resolved, measurement of temperature in gases.
- Provides an order of magnitude improvement in precision over existing optical methods.
- Improvements in accuracy will be achieved by using appropriate equation of state to derive the temperature using accurate models of the flame constituents.

Measurements on the NPL STD flame will commence later this year.

WP4: Traceable Combustion Temperature Measurement

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Summary and outlook

- NPL:
  - Portable STD flame developed
  - Traceable Laser Rayleigh scattering thermometry system commissioned
  - STD flame fully characterised – $U_r(T) \approx 0.5$ %
- UC3M:
  - Demonstration of Hyperspectral imager in STD flame
  - Good agreement with STD flame
  - Data interpretation ongoing
- DTU
  - UV absorption spectra: hot gas cells / flames
  - New absorption cross-sections for High-T, combustion applications
  - Simple analytical expressions for T vs absorption cross sections
  - Measurements on NPL STD flame later this year
- UOX:
  - LIGS demonstrated with flame generated NO (T ≈ 2300 K)
  - Developing infra-red LIGS to measure H_2O in the post-flame zone
  - Measurements on NPL STD flame later this year

Thank you

Department for Business, Energy & Industrial Strategy

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NPL: Combustion Temperature Standard

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Uncertainty budget: Rayleigh scattering thermometry

Table A1 Uncertainty budget for the temperature 20 mm above the centre of the NPL STD flame.

Source	**Type**	**Distr.**	**Size / ± %**	**Multiplier**	**Sensitivity Coefficient**	**Size (1σ) / %**
Molar refractivity data	B	Rect	0.20	0.58	1.00	0.12
Flow-meter uncertainty	B	Rect	1.00	0.58	0.40	0.23
Chemical equilibrium assumption	B	Rect	0.30	0.58	1.00	0.17
Air calibration PRT	A	Norm	0.05	1.00	1.00	0.05
Background scattered signal	A	Norm	0.10	1.00	0.50	0.05
Laser stability	A	Norm	0.20	1.00	1.00	0.20
Inlet air temperature (15-25 °C)	B	Rect	3.00	0.58	0.10	0.17
Atmospheric pressure	B	Rect	5.00	0.58	0.05	0.15
Gas purity	B	Rect	2.50	0.58	0.05	0.07
Flame temperature reproducibility	A	Norm	0.20	1.00	1.00	0.20
Total uncertainty (combined in quadrature)						**0.50 %**